

LIMITS ON PLANET FORMATION AROUND YOUNG PULSARS AND IMPLICATIONS FOR SUPERNOVA FALLBACK DISKS

M. KERR^{1,2}, S. JOHNSTON¹, G. HOBBS¹, AND R. M. SHANNON¹*Draft version July 28, 2015*

ABSTRACT

We have searched a sample of 151 young, energetic pulsars for periodic variation in pulse time-of-arrival arising from the influence of planetary companions. We are sensitive to objects with masses two orders of magnitude lower than those detectable with optical transit timing, but we find no compelling evidence for pulsar planets. For the older pulsars most likely to host planets, we can rule out Mercury analogues in one third of our sample and planets with masses $>0.4 M_{\oplus}$ and periods $P_b < 1$ yr in all but 5% of such systems. If pulsar planets form primarily from supernova fallback disks, these limits imply that such disks do not form, are confined to <0.1 AU radii, are disrupted, or form planets more slowly (>2 Myr) than their protoplanetary counterparts.

Subject headings: pulsars:general, planets and satellites:formation

1. INTRODUCTION

Somewhat surprisingly, the first extra-solar planets were detected in orbit around the millisecond pulsar PSR B1257+12 (Wolszczan & Frail 1992). Since then, optical observers have honed their techniques to the point where thousands of planets have now been detected around virtually all stellar classes (e.g. Wright et al. 2011; Rowe et al. 2014). Meanwhile, in spite of potentially high sensitivity to low-mass planets (Thorsett & Phillips 1992; Cordes 1993), the radio pulsar community has turned up only one further case, a super-Jupiter in a triple system within a globular cluster (PSR B1620–26, Sigurdsson et al. 2003).

Why is this so? First, a Galactic field pulsar planet must either have survived a supernova or have formed from the debris of the explosion. Phinney & Hansen (1993) give a delightful review of these “Salamander” and “Memnonides” scenarios, of which we consider planet formation in a supernova fallback disk (Lin, Woosley & Bodenheimer 1991) the most relevant mechanism. Here, reverse shock waves generated at density transitions in the stellar core and envelope decelerate material that falls back toward the compact remnant (Chevalier 1989). The total mass, accretion rate, and intrinsic angular momentum depend sensitively on both the initial stellar conditions and mixing during the explosion, but ultimately $\sim 0.1 M_{\odot}$ of material may circularize into a relatively long-lived “debris” disk (Menou, Perna & Hernquist 2001b). Wang, Chakrabarty & Kaplan (2006) observed a distinct infrared component from the anomalous X-ray pulsar 4U 0141+61, consistent with the reprocessing of X-ray emission by a warm disk, but other direct disk searches have failed to locate further examples (e.g. Wang et al. 2014).

Secondly, pulsars are far from perfect clocks. A companion induces a neutron star reflex motion detectable as a periodic delay in the pulse time-of-arrival (TOA). But pulsars suffer large amplitude, red timing noise (Shannon & Cordes 2010) and glitches which can mask such

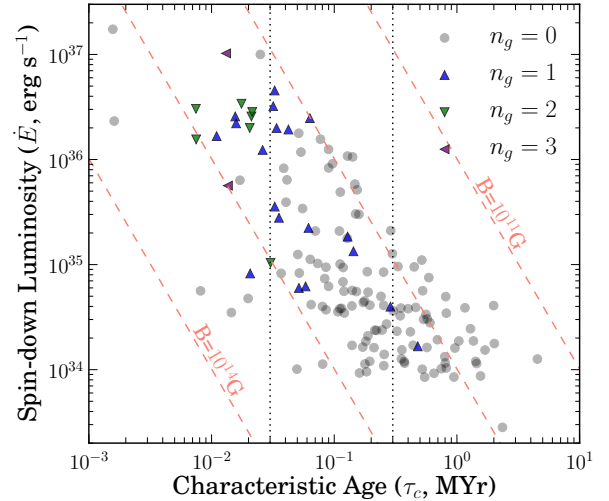


Figure 1. The spin-down power ($\dot{E} \equiv 10^{45} \dot{P}/P^3$ erg s^{−1}) and characteristic ages ($\tau_c \equiv P/2\dot{P}$ s) of the 151 pulsars in the sample. The sample divisions (see main text) in τ_c are indicated by the vertical lines. Pulsars suffering large glitches ($\delta\nu/\nu > 10^{-7}$) during our observation span are indicated by coloured, distinct symbols (legend). Lines of constant magnetic field ($B = 3.2 \times 10^{19} (P\dot{P})^{1/2}$ G) are shown as dashed salmon lines.

periodic signals. In addition, correlations between pulse shape and timing residuals indicate quasi-periodic state switching (Lyne et al. 2010; Hobbs, Lyne & Kramer 2010) with time-scales of months to years, mimicking the signature of planets. Finally, planets with very short or very long periods can evade detection due to finite observing cadences and data spans, respectively.

To further investigate the paucity of pulsar planets, we have searched for periodic signals in a sample of 151 energetic (spin-down luminosity $\dot{E} > 10^{34}$ erg s^{−1}) pulsars timed with the Parkes telescope in support of the *Fermi* mission. The \dot{E} and characteristic age τ_c of the sample are shown in Figure 1. These young pulsars tend to glitch regularly and are also subject to strong timing noise, complicating the search for planets with periods much longer than a year. However, given the an-

¹ CSIRO Astronomy and Space Science, Australia Telescope National Facility, PO Box 76, Epping NSW 1710, Australia

² email: matthew.kerr@gmail.com

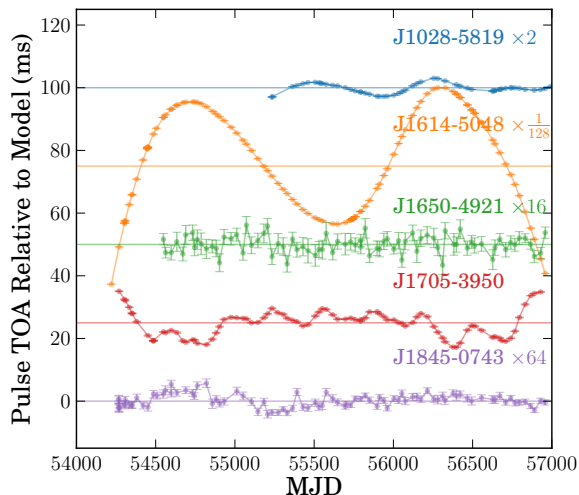


Figure 2. The deviation of TOAs of five pulsars to a simple spin-down model including $\ddot{\nu}$ to reduce low-frequency timing noise. The pulsars are chosen to illustrate the range of red and white noise in the sample, and residuals have been scaled by the indicated amount to facilitate comparison.

gular momentum budget ($\sim 10^{49}$ ergs) of a fallback disk, any Earth-mass planets should reside within ~ 2 AU of the neutron star, making our insensitivity to long periods unimportant for searching for planets formed in such disks. Moreover, the age range of our sample precisely spans the lifespan of an active disk and subsequent planet formation.

Below, we present a new technique (§2) for jointly modelling stochastic timing noise with other timing parameters which improves the robustness of detections of and upper limits on periodic signals. We derive upper limits (§3) for a range of periods for each member of our sample and present the combined constraints on the young pulsar population. We interpret the limits and their implications for supernova fallback debris disks in §4 and we summarize our results in §5.

2. DATA ANALYSIS

Our data comprise monthly timing observations with the Parkes telescope of 151 pulsars, largely identical to those given by Weltevrede et al. (2010). The bulk of these observations are carried out with the 20 cm multi-beam receiver, with 256 MHz of bandwidth centred at 1369 MHz digitally polyphase filterbanked into 1024 channels and folded in real-time into 1024 phase bins. Observation lengths t_{obs} range from 2–20 minutes depending on the flux density and sharpness of the pulse profile. Data typically span the seven years from 2007 June to 2014 Oct, and within this interval we supplement our observations with archival data where available.

For each pulsar, we have determined the best timing model, typically comprising spin-down terms ν and $\dot{\nu}$, the pulsar position, and, where required, proper motion and glitch parameters. A representative sample of the timing residuals to such a model (including a $\ddot{\nu}$ term) appears in Figure 2. The pulsars are strongly affected by red “spin” noise, and to estimate these parameters robustly requires modelling the resulting covariance between TOA measurements. We assume the red noise process is wide-sense stationary and model its power spectral

density as

$$P(f) = A_0 [1 + (f/f_c)^2]^{-\alpha/2}. \quad (1)$$

Here, f_c allows a possible low-frequency cutoff to the timing noise, while α describes its shape. By the Wiener-Khinchin theorem, $P(f)$ is the Fourier transform of $C(\tau)$, the covariance between TOAs separated in time by an interval τ . To this $C(\tau)$ we add the white noise model, a diagonal covariance matrix comprising measurement uncertainty and “jitter” noise (Shannon et al. 2014), which we model as $\sigma_j^2 = \beta/t_{\text{obs},j}$. The complete covariance matrix C can be written as a Cholesky decomposition, $C = LL^*$, with L a lower triangular matrix. If the noise model is accurate, L transforms the TOAs into unit variance normal random variables (Coles et al. 2011). The timing noise and jitter parameters, together with the pulsar timing parameters, form a complete model, and with the Cholesky decomposition we can efficiently evaluate its log likelihood. We apply Monte Carlo Markov Chain methods (MCMC, Foreman-Mackey et al. 2013) to determine its maximum and shape, yielding estimators for the parameters and their statistical uncertainty. We generally find this approach results in an acceptable fit, as evidenced by the successful whitening of the residuals, justifying our adoption of a power-law red noise model.

To characterize the reflex motion due to a single planet, we add to the above model the five Keplerian parameters (orbital period P_b , projected semi-major axis a , epoch of periastron T_0 , eccentricity e , and longitude of ascending node Ω) that fully define the orbit. We restrict the parameter space to $0 < e < 0.3$ (with uniform prior) and $56 < P_b$ (d) < 5000 . This is roughly the range of eccentricity expected from oligarchical planet formation scattering (see §4). The lower P_b bound is critically sampled with our monthly observing cadence, while the upper bound is roughly twice the data span. This is a substantial parameter space, and to ensure we explore it fully, we divide it into three subspaces: $56 < P_b$ (d) < 341 , $341 < P_b$ (d) < 393 , and $393 < P_b$ (d) < 5000 , a division motivated below. Following a lengthy burn-in period for the Markov chains to “forget” their initial conditions, we draw 1.2×10^6 samples from the first subspace and 6×10^5 samples from the latter two to form our final MCMC sample.

To search for planets, we computed the change in the log likelihood $\delta \log \mathcal{L}$ between the null (no planet) model and the best-fitting planet model over P_b bins. The value $\delta \log \mathcal{L}$ for a given planet mass depends strongly on the level of white and red noise, but with simulations we established $\delta \log \mathcal{L} \approx 12$ as a reasonable universal threshold for a significant detection.

Restricting attention to candidates with $P_b < 2$ yr, we found significant modulation in five pulsars, with the timing residuals of one, PSR J1705–3950, appearing in Figure 2. There are two strong arguments suggesting these are not pulsar planets. First, the implied masses are as great as $6 M_\oplus$, and such objects would be easily detected, but have not been, in samples including older pulsars with little timing noise (e.g. Hobbs, Lyne & Kramer 2010). Second, three show evidence for a significant second harmonic, similar to the well-known state switching PSR B1828–11 (Stairs, Lyne & Shemar 2000; Lyne et al. 2010), inviting a magnetospheric interpretation. If these

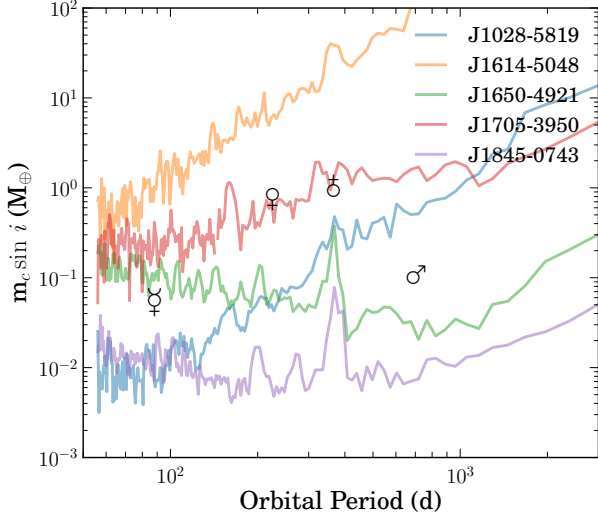


Figure 3. The 90% containment interval of the posterior distribution for companion mass, for five representative pulsars, as a function of companion period. Symbols indicate the masses and orbital period for inner solar system planets Mercury, Venus, Earth, and Mars.

harmonics are instead interpreted as two-planet systems, the resulting 2:1 mean motion resonance is dynamically unstable for the mass ratios (Beaugé, Ferraz-Mello & Michtchenko 2003). We will present a detailed analysis and interpretation of these modulations in a future work, but emphasize here the key conclusion, that these modulations are unlikely to represent *bona fide* planets, and that the small number of candidates ensures that the upper limits we compute below remain valid.

3. UPPER LIMITS ON PLANET MASSES

The Keplerian parameter a is related to the companion mass by the mass function:

$$\frac{m_c \sin i}{M_\oplus} = \frac{a}{1.50 \times 10^{-3} \text{ lt s}} \left(\frac{M_*}{M_\odot} \frac{1 \text{ yr}}{P_b} \right)^{2/3}, \quad (2)$$

where we have assumed $m_c \ll M_*$, with M_* the neutron star mass. While masses of isolated neutron stars are generally unknown, measurements from unrecycled binary systems suggest the Chandrasekhar mass $M_* = 1.4 M_\odot$ is representative (e.g. Lattimer 2012). If the plane of the putative binary is randomly orientated, i.e. $p(i) = \sin i$, then the mean and median values of $\sin i$ are $\pi/4 = 0.785$ and 0.866 respectively. We report projected mass values $m_c \sin i$, so physical masses corresponding to our upper limits will typically be 15% greater.

Several examples of the resulting planet limits, as a function of P_b , are shown in Figure 3. As noted by Thorsett & Phillips (1992), the general features of these spectra reflect simple physics and the relative strength of the white and red noise. The high-frequency limit is set by white noise in the data, in turn set by the observing cadence and the TOA precision. In the absence of red noise, this limit scales as $P_b^{-2/3}$ following Equation 2. The sinusoid induced by planets with $P_b \approx 1 \text{ yr}$ can be absorbed by shifting the apparent pulsar position, resulting in a dramatically reduced sensitivity. However, because we generalize our model to include $0 < e < 0.3$, sensitivity at these time-scales is actually *improved* rel-

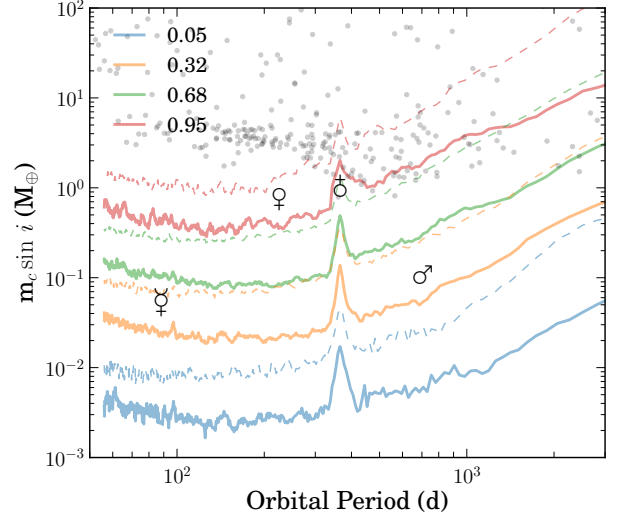


Figure 4. Limits on planet masses for pulsars with $\tau_c > 0.3 \text{ Myr}$ (solid lines) and $0.03 < \tau_c / \text{Myr} < 0.3$ (dashed, faint lines). The lines indicate the fraction of the posterior distribution of companion mass, for each period bin, contained below. The grey points correspond to confirmed exoplanets, primarily from Kepler, and are taken from the Exoplanet Database (Wright et al. 2011).

ative to the circular orbit case. Finally, the partial sinusoid of a long-period planet is similar to a parabola and is degenerate with ν , $\dot{\nu}$, and the realization of timing noise, admitting large values of a . Our division into three subspaces reflects this behaviour.

Figure 3 shows the range of typical cases. PSRs J1028–5819 and J1614–5048 are both affected by red noise and their sensitivity decreases monotonically with increasing P_b , but the low white noise level for J1028–5819 allows good sensitivity to short-period objects like Mercury. PSR J1016–5819 has a relatively high white noise level but very little red noise, and the favorable scaling of sensitivity with P_b yields good sensitivity to objects with $P_b > 1 \text{ yr}$, like Mars. Finally, J1845–0743 offers low noise at all frequencies and provides good sensitivity to every inner solar system analogue.

We can extract a posterior probability distribution for the entire population by assuming each pulsar is equally likely to host a planet. Then the posterior distribution of companion mass in a period bin is simply the sum of the individual distributions. Because we do in fact expect different pulsar ages to correspond to different stages of disk activity and planet formation, we have divided our sample into three bins of characteristic age (τ_c in Myr): $\tau_c > 0.3$ (47 pulsars); $0.03 < \tau_c < 0.3$ (84); and $\tau_c < 0.03$ (20). Our primary result appears in Figure 4, where we have constructed posterior distributions for the first two τ_c bins. The curves show the companion mass below which the indicated fraction of the posterior distribution is contained. They can be interpreted as limits on the occurrence of planets of a given mass: there is only a 5% chance a planet as massive as those indicated by the uppermost curve could reside in our sample, etc. For completeness, we performed a similar analysis using a frequentist method (profile likelihood) but assuming circular orbits, and we obtained similar results when considering the 95% confidence upper limits of the population.

The oldest pulsars provide the tightest constraints, and these are the most likely to harbor planets, having had sufficient time for disk evolution and planet formation. In this population, we conclude that planets of $0.1\text{--}0.2\text{ M}_{\oplus}$ and $P_b < 1\text{ yr}$ are absent from at least two thirds of the sample, and planets with $M > 0.6\text{ M}_{\oplus}$ can occur in no more than 5% of systems. Consequently, planet formation within $\approx 1.4\text{ AU}$ of neutron stars is at best a rare phenomenon.

Younger systems ($0.03 < \tau_c < 0.3$) provide similar but somewhat poorer constraints: planets exceeding 0.3 M_{\oplus} are absent from at least 2/3 of our sample, and planets of mass $1\text{--}1.5\text{ M}_{\oplus}$ must be rare, present in no more than 5% of cases. The youngest systems ($\tau_c < 0.03$) have low sensitivity due to their substantial timing noise. We expect such systems are also too young for planet formation (see §4), but for completeness, we note that our limits rule out planets of $1\text{--}2\text{ M}_{\oplus}$ in 68% of the very young sample.

4. IMPLICATIONS FOR DEBRIS DISKS

Our upper limits clearly show that Earth-mass planets are rare or absent within the first $\sim 2\text{ Myr}$ of the formation of a pulsar. What implication, if any, does this result have for the presence of debris disks around neutron stars? Following Phinney & Hansen (1993) and Miller & Hamilton (2001), we consider it unlikely that any original planets with periastron $< 1\text{ AU}$ could have survived immersion in the stellar envelope or remained bound after the supernova kick, and we concentrate on *in situ* planet formation.

First, we must ask: does our sample trace the young pulsar distribution? Our sample excludes magnetars and other obviously young but low- \dot{E} neutron stars, e.g. the weakly magnetized compact central objects (Halpern & Gotthelf 2010). However, Watters & Romani (2011) and other authors have argued that γ -ray pulsars, with properties similar to our sample, require the bulk of Milky Way supernova activity to account for their numbers. We therefore believe our selection of high- \dot{E} pulsars presents a minimally biased view of the young pulsar population, but it does not constrain disk formation around less typical neutron stars.

Secondly: given a disk with sufficient mass and angular momentum (radius), does planet formation occur efficiently and produce palpable planets? Fallback disks differ from protoplanetary disks in a key aspect: there is no external source of material. Thus, we appeal to a study aimed at reproducing the properties of planets around PSR B1257+12. Hansen, Shih & Currie (2009) found that disks with fallback-like angular momenta and layered viscous accretion can produce Earth-mass planets rapidly ($10^5\text{--}10^7\text{ yr}$) at inner solar system scales and with relatively small ($e < 0.2$) eccentricities. Even more encouragingly, they found that annular density profiles produced planets of a few M_{\oplus} in $< 1\text{ Myr}$. Such profiles might result if dust agglomerates into grains quickly after condensation during disk expansion, in which case the disk can deposit most of its dust at the same radius. In these scenarios, two or three planets with mass $1\text{--}3\text{ M}_{\oplus}$ populate the inner AU, along with a few residual planetesimals, and would be easily detectable in our sample.

Thus, we can say that *if* such disks are common around young neutron stars, at least some should host Earth-

mass planets and we should detect such in our sample. Moreover, even if rapid sedimentation does not proceed and the mass profile remains more homogeneous, Hansen, Shih & Currie (2009) find the production of detectable planets is still inevitable and merely proceeds on a $1\text{--}10\text{ Myr}$ time-scale. The absence of Earth-mass planets in both our sample and in larger samples including pulsars with $\tau_c > 10^7\text{ yr}$ (Hobbs, Lyne & Kramer 2010) seems to rule out such disks.

However, such disks seem to play an important rôle, at least in the pulsar literature. Debris disks have been advanced as triggering magnetospheric reconfiguration (Cordes & Shannon 2008; Brook et al. 2014; Kerr et al. 2014), altering the spin-down histories of pulsars (Menou, Perna & Hernquist 2001a; Yan, Perna & Soria 2012), contributing to pulsar timing noise (Shannon et al. 2013), and even enabling the pulsar mechanism (Michel & Dessler 1981). Chatterjee, Hernquist & Narayan (2000), among others, have speculated that normal pulsars accreting from a fallback disk may provide the X-ray emission observed in anomalous X-ray pulsars. They may also be responsible for some cases of peculiar supernova light curve evolution (Dexter & Kasen 2013).

Can we save this picture by forming disks that evade our upper limits? After an initial period of super-Eddington accretion, a fallback disk evolves self-similarly provided it remains viscous, transporting angular momentum and a small fraction of the material beyond the tidal disruption radius where planet formation can occur. The magneto-rotational instability (Balbus & Hawley 1991) is generally thought to provide this viscosity so long as the disk remains ionized, but as it cools, thermal ionization instabilities result in rapid condensation, leaving an inactive dust disk (Menou, Perna & Hernquist 2001b). (Though we note accretion may continue via an active central “layer”, in which case Currie & Hansen (2007) find the disk can reach the right scale for planet formation.) The final radius of such a debris disk depends sensitively on metallicity, and high-metallicity disks generally became inactive at small radii ($< 10^{10}\text{ cm}$), within the tidal disruption radius. Such disks could still form planets, but would first require scattering to move material beyond the tidal disruption radius. Moreover, this process is impeded by ablation of small bodies by the energetic pulsar wind (Miller & Hamilton 2001) and cannot proceed until the pulsar’s spin-down power \dot{E} drops low enough.

On the other hand, near impact on a companion from a supernova kick could form a debris disk with large angular momentum (Phinney & Hansen 1993), giving rise to planets with periods too long to be reliably detected in our analysis. We expect such events to be rare, as even in tight binaries the solid angle presented by an unevolved companion is small, and simulations suggest most binaries will have $P_b > 10\text{ d}$ (Terman, Taam & Savage 1998). Our sample contains only two binary systems, supporting the idea that most sample members did not form in close binaries.

Finally, it may be that long-lived debris disks simply fail to form. Stellar material may fall back onto the compact remnant but ultimately be ejected by a propeller phase (Ekşi, Hernquist & Narayan 2005). Or, the pre-supernova conditions may be such that the specific

angular momentum of the stellar core is too low to circularize. In this case, the explosion energy either unbinds the entirety of the star, leaving a neutron star, or a huge amount of material falls back, triggering a collapse to a black hole. Recent one-dimensional numerical simulations by Perna et al. (2014) suggest that magnetic coupling saps the specific angular momentum of the stellar core to such a degree that only fine-tuned explosions can produce appreciable fallback onto a neutron star, and the resulting disk lasts only a few hundred seconds.

5. SUMMARY AND CONCLUSION

We have searched a large sample of young pulsars for periodic modulation characteristic to planetary companions. Our work is an improvement on previous efforts (Thorsett & Phillips 1992), as our pulsar sample is two orders of magnitude larger and we employ sophisticated methods to mitigate pulsar timing noise and model realistic (noncircular) orbits. Despite the good sensitivity to low-mass planets we find no compelling evidence for such systems. We argue that such companions could have formed in debris disks within the 2 Myr age range spanned by our sample, and their absence implies supernova fallback disks are either rare or confined to small radii.

Whence, then, the planets of PSR B1257+12? Miller & Hamilton (2001) have argued PSR B1257+12 was born with its present 6 ms spin period and an intrinsically weak magnetic field. Such a weak field may point to atypically weak magnetic coupling in the progenitor stellar core, evading the constraints of Perna et al. (2014). If this is so, isolated millisecond pulsars with modest spin periods may make excellent targets for direct debris disk searches.

The Parkes radio telescope is part of the Australia Telescope, which is funded by the Commonwealth Government for operation as a National Facility managed by CSIRO.

REFERENCES

- Balbus S. A., Hawley J. F., 1991, *ApJ*, 376, 214
 Beaugé C., Ferraz-Mello S., Michtchenko T. A., 2003, *ApJ*, 593, 1124
 Brook P. R., Karastergiou A., Buchner S., Roberts S. J., Keith M. J., Johnston S., Shannon R. M., 2014, *ApJ*, 780, L31
 Chatterjee P., Hernquist L., Narayan R., 2000, *ApJ*, 534, 373
 Chevalier R. A., 1989, *ApJ*, 346, 847
 Coles W., Hobbs G., Champion D. J., Manchester R. N., Verbiest J. P. W., 2011, *MNRAS*, 418, 561
 Cordes J. M., 1993, in *Astronomical Society of the Pacific Conference Series*, Vol. 36, *Planets Around Pulsars*, Phillips J. A., Thorsett S. E., Kulkarni S. R., eds., pp. 43–60
 Cordes J. M., Shannon R. M., 2008, *ApJ*, 682, 1152
 Currie T., Hansen B., 2007, *ApJ*, 666, 1232
 Dexter J., Kasen D., 2013, *ApJ*, 772, 30
 Ekşi K. Y., Hernquist L., Narayan R., 2005, *ApJ*, 623, L41
 Foreman-Mackey D., Hogg D. W., Lang D., Goodman J., 2013, *PASP*, 125, 306
 Halpern J. P., Gotthelf E. V., 2010, *ApJ*, 709, 436
 Hansen B. M. S., Shih H.-Y., Currie T., 2009, *ApJ*, 691, 382
 Hobbs G., Lyne A. G., Kramer M., 2010, *MNRAS*, 402, 1027
 Kerr M., Hobbs G., Shannon R. M., Kiczynski M., Hollow R., Johnston S., 2014, *MNRAS*, 445, 320
 Lattimer J. M., 2012, *Annual Review of Nuclear and Particle Science*, 62, 485
 Lin D. N. C., Woosley S. E., Bodenheimer P. H., 1991, *Nature*, 353, 827
 Lyne A., Hobbs G., Kramer M., Stairs I., Stappers B., 2010, *Science*, 329, 408
 Menou K., Perna R., Hernquist L., 2001a, *ApJ*, 554, L63
 Menou K., Perna R., Hernquist L., 2001b, *ApJ*, 559, 1032
 Michel F. C., Dessler A. J., 1981, *ApJ*, 251, 654
 Miller M. C., Hamilton D. P., 2001, *ApJ*, 550, 863
 Perna R., Duffell P., Cantiello M., MacFadyen A. I., 2014, *ApJ*, 781, 119
 Phinney E. S., Hansen B. M. S., 1993, in *Astronomical Society of the Pacific Conference Series*, Vol. 36, *Planets Around Pulsars*, Phillips J. A., Thorsett S. E., Kulkarni S. R., eds., pp. 371–390
 Rowe J. F. et al., 2014, *ApJ*, 784, 45
 Shannon R. M., Cordes J. M., 2010, *ApJ*, 725, 1607
 Shannon R. M. et al., 2013, *ApJ*, 766, 5
 Shannon R. M. et al., 2014, *MNRAS*, 443, 1463
 Sigurdsson S., Richer H. B., Hansen B. M., Stairs I. H., Thorsett S. E., 2003, *Science*, 301, 193
 Stairs I. H., Lyne A. G., Shemar S. L., 2000, *Nature*, 406, 484
 Terman J. L., Taam R. E., Savage C. O., 1998, *MNRAS*, 293, 113
 Thorsett S. E., Phillips J. A., 1992, *ApJ*, 387, L69
 Wang J. B. et al., 2014, *ArXiv e-prints*
 Wang Z., Chakrabarty D., Kaplan D. L., 2006, *Nature*, 440, 772
 Watters K. P., Romani R. W., 2011, *ApJ*, 727, 123
 Weltevrede P. et al., 2010, *Publ. Astron. Soc. Australia*, 27, 64
 Wolszczan A., Frail D. A., 1992, *Nature*, 355, 145
 Wright J. T. et al., 2011, *PASP*, 123, 412
 Yan T., Perna R., Soria R., 2012, *MNRAS*, 423, 2451